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28 TOPSOIL AND SNOW: A CONTINUUM SYSTEM

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34 Abstract

35 Snow cover plays a fundamental role in terrestrial ecosystems, because it influences the Earth's climate, water quantity
36 and quality, global biogeochemical cycles and soil properties. In particular, snow helps to create and maintain a specific
37 pedo-environment through its influence on pedogenesis and topsoil characteristics, such as the thermal and water regimes
38 and soil biogeochemistry. Importantly, seasonally snow covered regions are particularly susceptible to climate change,
39 which could alter the timing and the quality of snow cover, with consequences on ecosystems and pedo-environments.

40 **Keywords:** soil temperature; carbon; nitrogen; ski runs; snow gliding.

41 1. Introduction

42
43 Seasonal snow cover and soil frost affect about 60% of the terrestrial earth surface, ranging from high latitude tundra and
44 forest biomes to mid-latitude forests and grasslands biomes, and includes many mountain regions (Zhang et al. 2004;
45 Brooks et al. 2011). Seasonal snow cover is an important part of Earth's climate system, and in fact helps regulate the
46 temperature of the Earth's surface because of its high albedo. The insulating properties of snow influence the underlying
47 soil temperature regime and the extent to which soil is directly exposed to freezing and thawing episodes (Edwards et al.,
48 2007). In forest and tundra greater snow depth insulates soils from cold air temperatures and allows higher levels of
49 microbial nitrogen immobilization under snow, as well as decreases soil N₂O efflux (Li et al. 2016), while shallower
50 snowpacks are associated with higher hydrologic nitrogen export (Brooks et al., 2011). Both CO₂ and CH₄ flux studies
51 during winter demonstrate active carbon (C) cycling under seasonal snowpacks in different ecosystems (Brooks et al.,
52 2011). Snow also accumulates significant amounts of particulates and solutes due to atmospheric deposition, which can
53 be rapidly released during spring melt in the form of an ionic pulse (Filippa et al., 2010). Therefore, the seasonal snowpack
54 has the potential to exert a significant impact not only on terrestrial but also on aquatic ecosystems (Edwards et al., 2007;
55 Williams et al., 2009). Brooks and Williams (1999) reported that more than half of the annual inorganic nitrogen (N)
56 deposition can be stored in the snowpack and released during snowmelt episodes. Nitrogen is flushed through the
57 snowpack at the beginning of snowmelt and, in combination with that released from soil mineralization, results in a pulse

of inorganic N under the snowpack (Edwards et al., 2007). The soil may function either as a source or sink of nutrients depending on the species involved and the extent to which snowmelt infiltrates (Brooks and Williams, 1999). The seasonally snow covered regions are particularly susceptible to climate change, because small changes in temperature or precipitation may result in large changes in the amount and timing of snow cover (Brooks et al. 2011). Climate change may affect the seasonal snow cover in several ways: higher temperatures result in a higher percentage of the precipitation falling as rain instead of snow, causing snow covers to be thinner and to melt earlier, a phenomenon already visible in many mountain ranges (e.g. Laternser and Schneebeli, 2003; Viglietti et al., 2014). Snow density is likely to increase in a warmer climate, as higher temperatures may cause wetter snow and increase the frequency of wet-snow avalanches which exert considerably erosive forces on soils (e.g. Rasmus et al., 2004; Ceaglio et al., 2012). Interestingly, a warmer climate will not necessarily result in warmer soils: a thinner and denser snow cover will reduce the insulation of the soil (Rixen et al., 2008a). Consequently, alpine ecosystems might face the counterintuitive situation that soils could become colder in winter in a warmer climate (Groffman et al., 2001). Given that soil and snow are obviously connected, they could be considered a continuous system, therefore an interdisciplinary approach is required, with competences from snow and soil scientists (Guyon G.L., 1978).

2. Snow cover and subnivean soil properties

2.1. SOIL TEMPERATURE AND MICROBIAL ACTIVITY

Snow is an excellent thermal insulator and consistent seasonal snow cover effectively decouples soil temperature from the air temperature (Edwards and Cresser, 1992) (Fig. 1). Soils typically experience freezing conditions during early winter, sometimes before a deep snow cover accumulates to protect the soils from low air temperatures, remaining in a partially unfrozen condition (+1 to -3°C) (Jones, 1999): biological activity is surprisingly high at temperatures approaching subzero, which are typical of these subnivean conditions (Federer et al. 1990; Mikan et al., 2002; Panikov et al., 2006). The presence of liquid water has been identified as an essential prerequisite for physiological activity of microbes in any environment, including soils at near or subzero temperatures (Coxson and Parkinson, 1987; Mikan et al., 2002). In addition microbial activity is strongly affected by the supply of labile organic carbon (Boddy et al., 2008; Brooks et al., 2005; Buckeridge and Grogan 2008) which during winter could be influenced by the effects of snow depth and soil thermal status on litter decomposition rates (Hobbie and Chapin, 1996; Sulkava and Huhta, 2003).

2.2. SNOWMELT AND SOIL NUTRIENT CYCLING

The mountain snowpack represents an important source of nutrients and water for soils, because it can accumulate significant amounts of wet and dry atmospheric deposition which may be held in storage until release during a melt period

(Filippa et al., 2010). In high-elevation areas, more than half of the year's N deposition is periodically stored in the snowpack (Hiltbrunner et al., 2005). Filippa et al. (2010) reported that in the NW Italian Alps dissolved inorganic N (ammonium and nitrate) stored in snow was comparable to concentrations found in other sites of the Alps, and corresponding to about 2–6% of the over-winter N mineralization in alpine soils. The melting of the snow cover defines the start and length of the growing season, and water and nutrients released from the snowpack influence soil moisture and nutrient status until later in the summer. Field and laboratory experiments have demonstrated that initial stages of snowmelt often have ionic concentrations many times higher than averages for the whole snowpack, referred to as an ionic pulse (Johannessen and Henriksen, 1978). Therefore, during snowmelt soluble inorganic N compounds and other N sources such as dust particles, are released into the soil in a relatively short time period, favouring the plant species which take up nutrients during snowmelt (Bilbrough and Welker 2000; Hiltbrunner et al., 2005).

2.3. SOIL GAS FLUXES

The interaction between snow cover and soil is also important for gaseous emission, because there is evidence that microbial activity and consequent emission of gaseous C and N continue in the relatively warm conditions that may occur in soils under a continuous snowpack (Sommerfeld et al. 1993; Brooks et al. 1996;). For example, Filippa et al. (2009) at Niwot Ridge, Colorado, found that during winter, the relatively well-developed soils together with prolonged deep snow cover, result in subnivean N₂O production that might account for between 19 and 28% of the annual flux. In summer N₂O fluxes followed a decreasing trend during the dry-out period after snowmelt, interrupted by higher values related to precipitation events which were identified as the main factors controlling N₂O flux. Both CO₂ and CH₄ flux studies during winter demonstrate active carbon cycling under seasonal snowpacks in different ecosystems, with a high sensitivity of fluxes to small changes in seasonal snow cover (Brooks et al., 2011).

3. Snow distribution, pedogenesis and soil properties

Wind redistribution of snow involves erosion of snow cover by the shear force of the wind, transport of blowing snow in transit, and deposition of snow to sites with higher aerodynamic roughness or less exposure to wind. In open environments, vegetation and terrain features can produce dramatic variations in snow accumulation by trapping wind-transported snow (Jones et al. 2001). The topographically defined snowpack distribution produces a spatial gradient in soil water availability, soil temperature and in the timing of soil dry-down following snowmelt (Taylor and Seastedt, 1994). The spatial variation of snow accumulation affects litter decomposition rates (O'Lear and Seastedt 1994), plant

118 communities distribution (Fisk et al. 1998) and productivity (Walker et al. 1994), and organic matter accumulation (Burns
119 and Tonkin 1982).
120 Freppaz et al. (2012) reported that after 16 years of snow distribution manipulation at Niwot Ridge (Colorado) under
121 moderate snow cover the total soil organic carbon (TOC) and total nitrogen (TN) were significantly greater than either
122 under deep or shallow snow cover. Depth and duration of the snow cover as well as vegetation influence site factors such
123 as soil moisture and soil temperature that are important to soil-forming processes (Holtmeier and Broll, 1992) (Fig. 2).
124 Studies conducted by Holtmeier and Broll (1992) provide evidence for distinct differences in pedogenesis and soil
125 properties due to microtopography and scattered tree islands, because their influence on windflow near the soil surface,
126 which in turn affects the distribution pattern of the winter snow cover. Schaetzl (1990) found a different degree of soil
127 development under pit and mound originated by tree uprooting. Pit exhibits a stronger pedogenesis than undisturbed and
128 mound soils explained by: a) the greater water content, which may facilitate weathering processes; b) thicker O horizons,
129 which may lead to increased production of organic acids; c) greater insulation by thick litter and snow cover, which
130 reduces the incidence of soil freezing. In addition, as reported by Pintaldi et al. (2016), differences in snow cover
131 distribution due to hummock microtopography could also contribute to create specific pedoclimatic conditions, enhancing
132 selective plant species distribution, variations on topsoil properties and different soil development under hummocks and
133 interhummocks.

134

135 **4. Seasonally snow-covered soils under a changing climate**

136 Increased air temperature due to climate change likely will result in shorter snow covered seasons due to later
137 accumulation and earlier melt (Brooks et al. 2011), with a general decrease in the spatial extent of spring snow cover in
138 the Northern Hemisphere (IPCC 2014), readily observable in an increase in elevation of the rain–snow line (Lundquist et
139 al. 2008). The reduction in snow cover, as well as its variations in density and thickness (Rixen et al. 2008a), reduces the
140 degree of insulation and results in cold soil temperatures, extensive soil freezing and an increase in freeze/thaw cycles
141 (Edwards and Cresser, 1992; Groffman et al., 1999) (Tab. 1). Several researchers reported the effects of freeze/thaw
142 cycles on soil processes such as an increase in fine root mortality (Tierney et al., 2001), a change in soil structure (Kværnø
143 and Øygarden, 2006), an influence on microbial activity (Grogan et al., 2004) and nutrient loss (Matzner and Borken,
144 2008). Freppaz et al. (2008) (LTER site Mont Mars) reported how a reduction in snowpack depth caused a significant
145 increase in soil net ammonification and net nitrification but did not affect microbial biomass N, revealing how soil freezing
146 could enhance soil-aggregate disruption, releasing physically protected soil organic matter and fragmentation of organic
147 matter itself (Tab. 1). Freeze-thaw events are known to release labile, readily utilizable, organic carbon compounds. The
148 effects of this increase in carbon substrate have been observed in the field when fluxes of CO₂ from seasonal snowpacks

149 increased exponentially following a severe, early winter freeze before the development of a consistent snowpack (e.g.
150 LTER site Niwot Ridge) (Brooks et al., 1997).

151

152 **5. Snow movements and soil properties**

153 Mountain areas are widely affected by soil erosion, which is generally linked to water runoff processes (Ceaglio et al.
154 2012). However, snowmelt runoff and snow movement related processes may also be important factors that can enhance
155 soil erosion (Konz et al., 2009; Ceaglio et al. 2012). The snow movements which effect soils are mainly snow gliding and
156 full-depth snow avalanches (Ceaglio et al. 2012). Additionally, the snowmelt period can contribute significantly to the
157 total annual runoff and sediment yield in streams and rivers. (Lana-Renault et al., 2011). These phenomena can exert
158 considerable erosive forces on soils; in particular avalanches can transport consistent amounts of debris, especially when
159 they involve the whole depth of snow or run onto snow-free areas (Freppaz et al., 2006, 2010; Confortola et al., 2011).
160 Deposits of debris from snow avalanches are common in mountain environments indicating the importance of avalanches
161 as specific geomorphic agents (Fig. 2). For example, Ceaglio et al., (2012), in the Aosta Valley of Italy, reported snow
162 related soil deposition rates of $161.0 \pm 34.8 \text{ Mgha}^{-1}$ for a single snow avalanche event, with a soil erosion rate of $20.8 \pm$
163 $4.5 \text{ Mgha}^{-1} \text{ event}^{-1}$, corresponding to a soil layer of $1.73 \pm 0.37 \text{ mm}$.

164 Soils can be eroded in different ways, depending on the avalanche type (Confortola et al., 2011). If full-depth avalanches
165 predominate, and the avalanche flows interact directly with the soil surface, the soils can be stripped off in the track zone
166 and can be fragmented and/or highly degraded (Freppaz et al., 2006, 2010) (Fig. 3). Complex soil profile morphologies
167 may occur along an avalanche path, with both buried or truncated horizons (King and Brewster, 1978; Stanchi et al.,
168 2014). If surface avalanches predominate, then soils in the transition zone are better preserved and the avalanche channels
169 can be completely grass-covered (Bozhinskiy and Losev, 1998). Also snow gliding phenomena can contribute
170 significantly to soil erosion at the snow–soil interface as shown by Meusburger et al. (2014), who identified snow gliding
171 as a relevant driver for winter soil erosion in the Swiss Alps. Changes in snow distribution due to snow avalanches help
172 shape plant and animal distribution, particularly in the deposition zone where the deeper snow represents a non-flowing
173 water storage during the winter, with specific chemical properties, which is released when the temperature increases
174 during the summer growing season (Luckman, 1977; Freppaz et al., 2010).

175

176

177 **6. Snow and soil characteristics in ski runs**

178 In the last decades in mountain regions the surface area converted to recreational activities has increased due to the
179 increasing demand of tourists for winter sports. To guarantee skiing despite unfavourable weather conditions,

180 snowmaking facilities have been installed in many ski resorts (Rixen et al. 2008a). To enhance ice crystal formation under
181 warmer temperatures, additives to enhance ice nucleation are increasingly used in snowmaking (Rixen et al., 2003).
182 Therefore, ski-run construction and management have a great influence on the chemical and physical properties of
183 underlying soils. For example, as reported by Rixen and Freppaz (2015), the average amounts of nutrient salts and ions
184 in the melting water is, on average, eight times higher on pistes with artificial snow. In addition, as well as additives, the
185 water used for artificial snow, such as calcium-rich water from down-elevation rivers, may have long term consequences
186 on soil and vegetation (Rixen et al., 2008b; Wipf et al., 2005). Freppaz et al. (2013) reported that soils in ski-runs have
187 an almost complete lack of structure, with subsequent problems of soil compaction and reduction of water and air
188 permeability, which enhances erosion on ski-runs. Snow plays an important role on ski-run soil processes, because
189 groomed snow is denser and thin compared to natural snow. These characteristics may result in reduced insulation
190 capacity of the snowpack and thus, the underlying ground may become much colder with subsequent effects on soil
191 nutrient dynamics and plant development (Freppaz et al. 2013). The soils of ski runs are thus subjected to more intense
192 freezing, higher CO₂ fluxes, and changes in pH and nitrogen fixation (Freppaz et al. 2013). Rixen et al. (2008a) found
193 that a denser and thinner snow cover reduced soil insulation and lowered soil temperatures, with a consequent increase in
194 net N mineralization (Tab. 1). Furthermore, a denser snow cover resulted in a delay in plant phenology of up to five weeks
195 after melt-out., therefore changes in snow properties linked to ski run management, can cause significant changes in soil
196 and vegetation processes (Rixen et al. 2008a).

197 198 **7. Conclusion**

199 Given the high number of studies, the effects of snow cover on mountain ecosystems in general, and in particular on soil
200 biogeochemistry is remarkable, especially in the perspective of climate change. This contribution revealed how in
201 mountain areas soil and snow should be considered a continuum, because of a strong and effective mutual interaction,
202 which is primarily reflected in the topsoil properties.

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205

206

207 **References**

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Figure Captions

Fig. 1. Mean daily topsoil temperature (10 cm depth, °C) at site 1 (snowbed site, 2840 m a.s.l.) and site 3 (windblown snow site, 2770 m a.s.l.) registered from Fall 2008 to Summer 2016 at the LTER site Istituto Mosso (Piemonte Region, NW-Italian Alps).

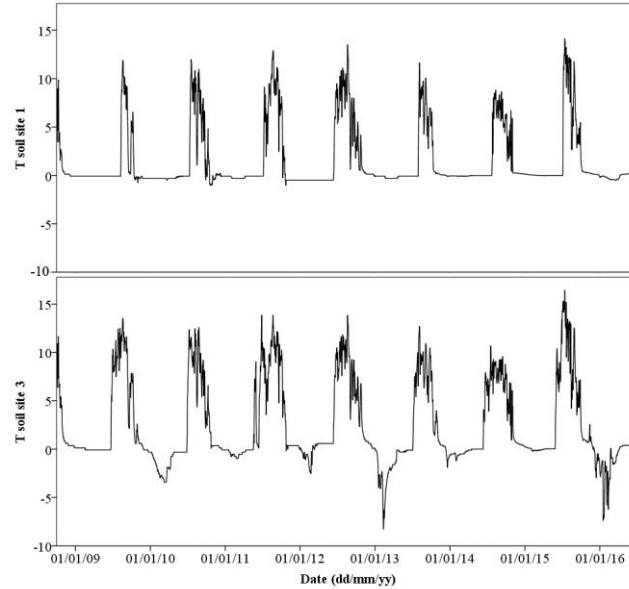


Fig. 2. A podzol under a thick snow cover in the LTER site Mont Mars (1840 m a.s.l., Valle d'Aosta Region, NW-Italian Alps) (Photo M. Freppaz).



Fig. 3. A Topsoil deposited in the run-out area of a glide-snow avalanche (Valle d'Aosta Region, NW-Italian Alps)

389 (Photo M. Freppaz).

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Country/Bioma	Elevation (m a.s.l.)	Topsoil C and N in the study area (ranges)	> snow depth	< snow depth	> snow density	Authors
Lys Valley (Aosta Valley-Italy)/Subalpine- Alpine forest-meadow	1450	TOC (g Kg ⁻¹) 12-39 TN (g Kg ⁻¹) 0. 5-3.1 DOC (mg Kg ⁻¹) 207.0-289.0 DON (mg Kg ⁻¹) 115.0-138.5	> T soil Net ammonification ↓ Net nitrification ↓	< T soil Net ammonification ↑ Net nitrification ↑		Freppaz et al. 2008
Niwot Ridge LTER site (Colorado-USA)/ Alpine tundra	3528	TOC (g Kg ⁻¹): 120-130 TN (g Kg ⁻¹): 8.0-9.0	TOC (g kg ⁻¹): ~ 90-100 TN (g Kg ⁻¹): ~ 8 pH: ~ 5.4 DOC (mg Kg ⁻¹): ~ 170 DON (mg Kg ⁻¹): ~13	TOC (g Kg ⁻¹): < 90 TN (g Kg ⁻¹): ~ 6 pH: ~ 5.6 DOC (mg Kg ⁻¹): ~ 178 DON (mg Kg ⁻¹): ~19		Freppaz et al. 2012
Bipenggou Nature Reserve of Lixian County (Sichuan- China)/ Alpine forest	3580	DOC (mg Kg ⁻¹): 240-250 DON (mg Kg ⁻¹): 50-55	DOC (mg Kg ⁻¹): ~ 250 DON (mg Kg ⁻¹): < 50	DOC (mg Kg ⁻¹): ~ 550 DON (mg Kg ⁻¹): ~ 100		Tan et al. 2014
Western Alps (Piedmont- Italy)/Subalpine forest	2030	TOC (g Kg ⁻¹): 59.3 TN (g Kg ⁻¹): 4.2 DOC (mg Kg ⁻¹): 250-331 DON (mg Kg ⁻¹): 9.2- 14.2	T soil: > 0° C DOC (mg Kg ⁻¹): < 400 DON (mg Kg ⁻¹): < 40	T soil: < 0° C DOC (mg Kg ⁻¹): > 400 DON (mg Kg ⁻¹):> 40		Viglietti et al. 2014
Rhaetian Alps, (Davos- Switzerland)/Subalpine meadow	1530				T soil: < 0° C > Net ammonification > Net N mineralization	Rixen et al. 2008a

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396 **Table 1.Examples of changes in topsoil C and N forms and temperature (Tsoil during winter) in different biomes due to**
397 **changes in snow characteristics (increase in snow depth: > snow depth; decrease in snow depth: < snow depth; increase in**
398 **snow density: > snow density).**

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